



Gas to Solid and Solid to Gas Reactions Visualized by Environmental TEM

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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Wagner, J. B. (2018). *Gas to Solid and Solid to Gas Reactions Visualized by Environmental TEM*. Abstract from MRS Spring meeting 2018, Phoenix, United States.

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A deep understanding of the formation mechanisms of low-dimensional nanostructures from bottom-up processes is of great importance in order to exploit the controllability of the nanostructures and their applications in photovoltaics, electronics, sensors, *etc.* on an industrial scale.

Environmental transmission electron microscopy allows for monitoring gas-solid reactions at the nanoscale in real time. Examples of such reactions includes growth of 2D materials (graphene)[1], pseudo 1D materials (carbon nanotubes)[2] and semiconductor oxides such as CuO[3].

The high spatial resolution combined with spectroscopic capabilities enables fundamental insights during the dynamical growth processes of the nanostructured materials directly linked to growth parameters such as atmosphere composition and temperature.

Growth and growth termination of single wall carbon nanotubes are very dependent on the local environment of the catalytic seed particle forming the tubes [4]. Topology of the seed particle support, the state of the catalytic particle, and carbon source play a crucial role in the growth dynamics. Observing the initial solid carbon formation on seed particles at the atomic scale reveals the conditions leading to encapsulation of the catalyst particles (no carbon nanotube growth) and a carbon layer lift-off resulting in nanotube growth, respectively.

Nanostructures can also be formed by simple oxidation of metals such as copper. CuO nanowires are formed by oxidation of metallic copper in situ in the electron microscope. The exact geometry of the resulting structures depends strongly on the partial pressure of oxygen during the heat treatment. Low pressure results in 2-dimensional copper oxidation in contrast to the 1-dimensional CuO nanowires forming at higher pressures. Post-growth treatment of the oxide nanowires at elevated temperature at reduced partial pressure of oxygen results in dissolution of the formed nanowires [5]. The direct observation of oxidation and disintegration reveals the nature of the facet dependent reactions.

Gas to Solid (growth) and Solid to Gas (disintegration) reactions directly visualized by means of controlled atmosphere electron microscopy is a key factor in the understanding of the formation mechanisms and thereby a stepping stone towards the controlled synthesis of tailored materials.

[1] J. Kling *et al.* Carbon 99, 261 (2016)

[2] M. He *et al.*, Scientific Reports 3, 1460 (2013)

[3] S. Rackauskas *et al.*, Nano Letters 14, 5810 (2014)

[4] L. Zhang *et al.* ACS Nano 11, 4483 (2017)

[5] S. Rackauskas *et al.*, Scientific Reports 7, 12310 (2017)